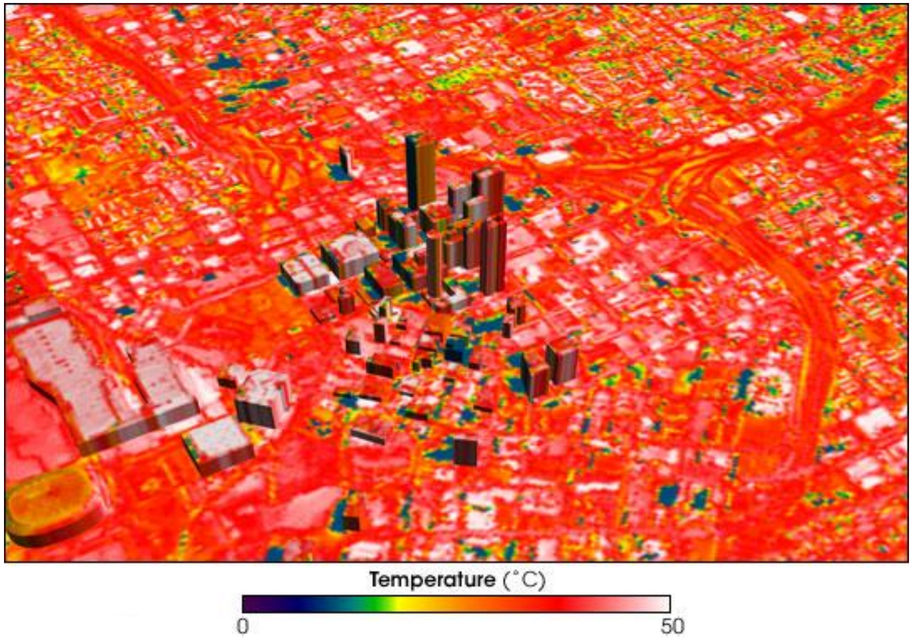
Modeling the Urban Energy Balance



<earthobservatory.nasa.gov>

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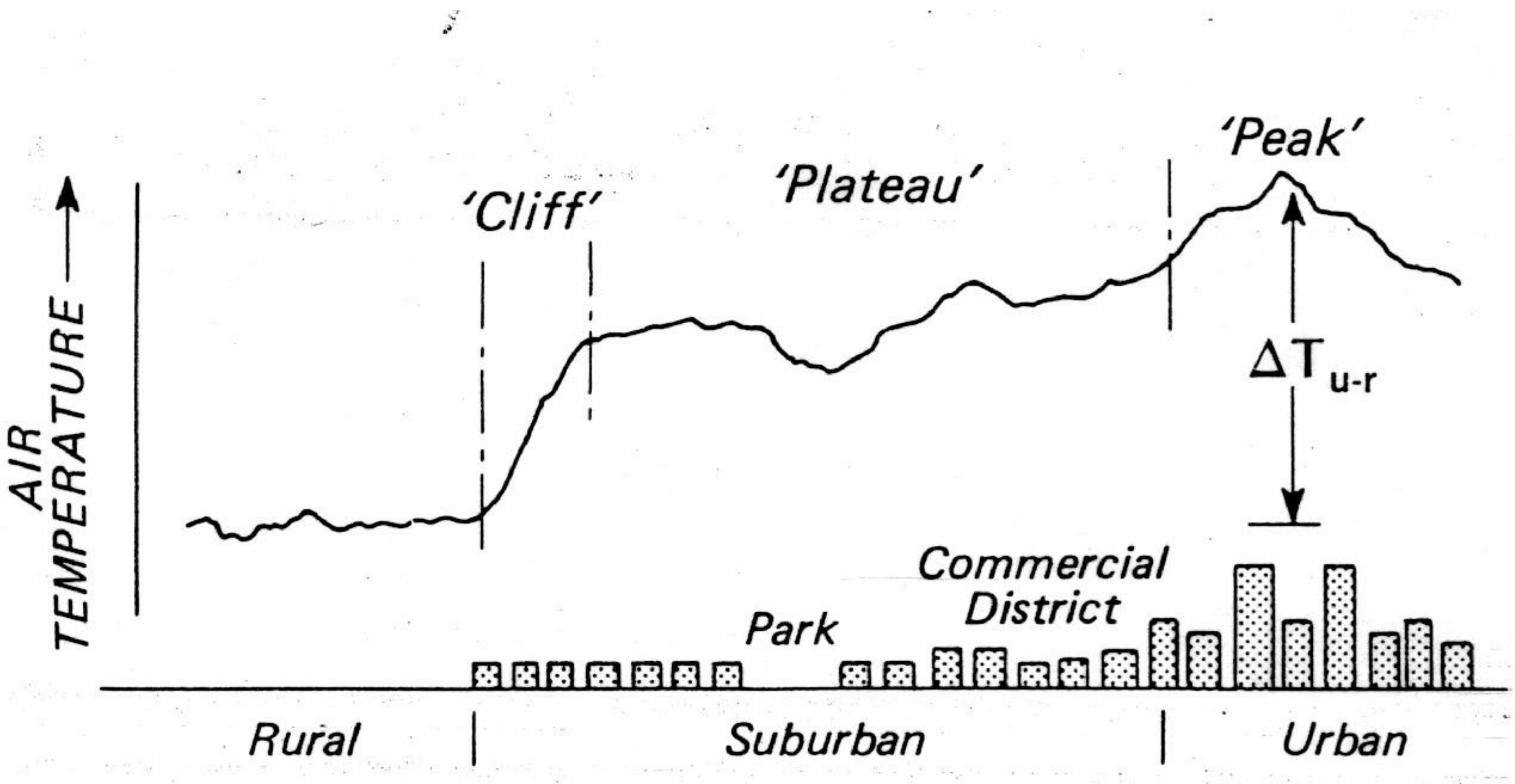
The Urban Heat Island (UHI) Effect



Oke (1987)

Factors Contributing to UHI Formation

- Urban Energy Balance Equation

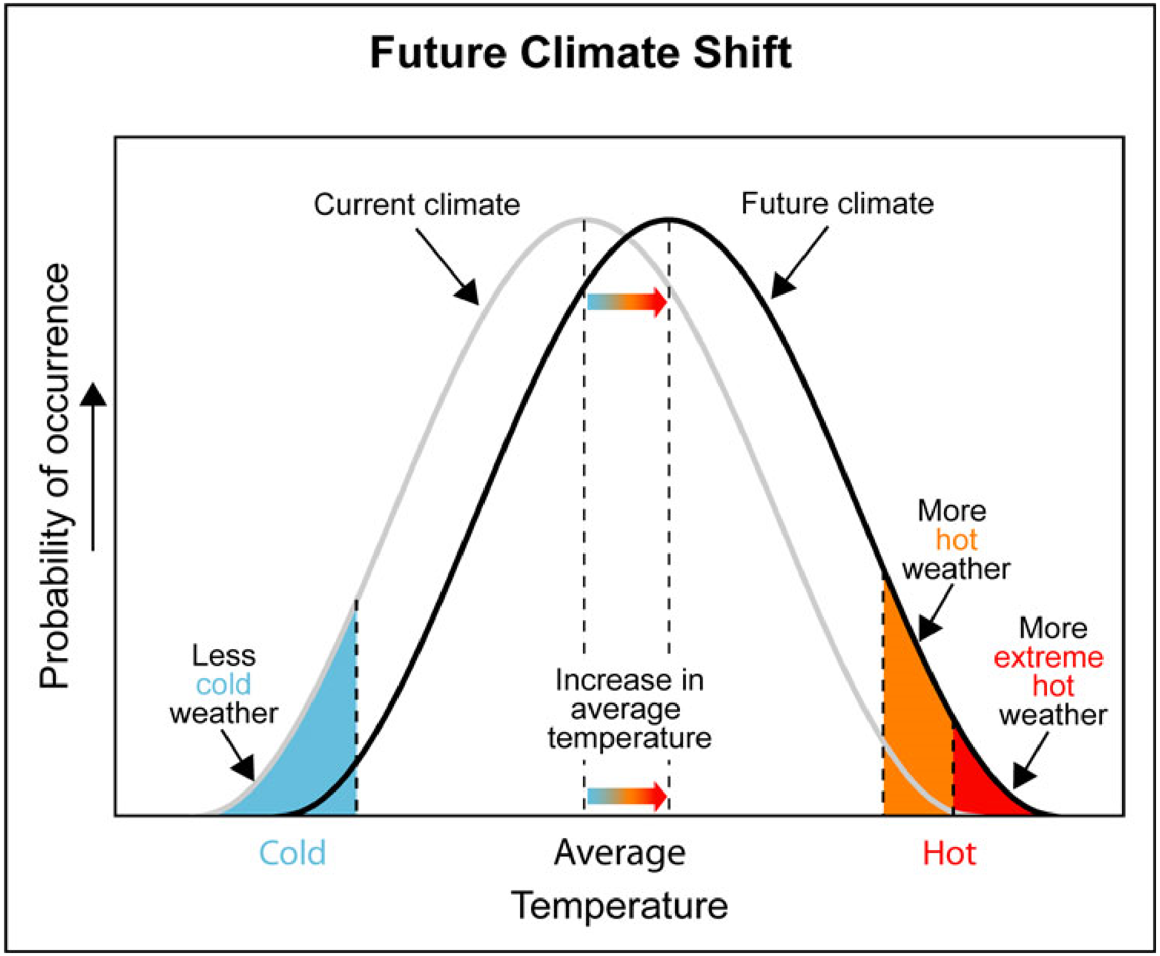
$$R_{net} + Q_A = Q_H + Q_E + Q_G + Q_S$$

- Reduction in latent cooling (e.g. vegetation non-permeable surfaces)
- Increased surface temperatures (e.g. low albedo, high heat capacity)
- Anthropogenic heat (e.g. cars, HVAC, people etc.)

Why should we care about UHIs?

- Electricity demand increases about 2-4% for every 1˚C rise in air temperature
  - U.S. building electricity use $613 billion in 2006 dollars
- Mortality increases during heat waves
  - 1995 extreme heat wave in Chicago, Illinois resulted in 700 heat related death
- Production of some green house gasses increases with temperature (e.g. smog => ozone)

Why should we care about UHIs?

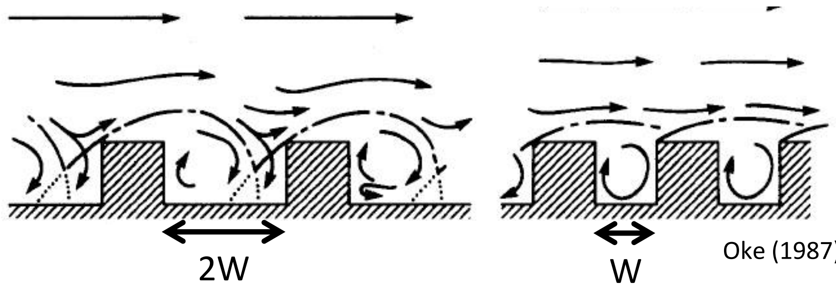


<southwestclimatechange.org>

What can/should we do about UHIs?

- UHI mitigation accomplished by **Green Design and Engineering**

<scholtensroofing.com>

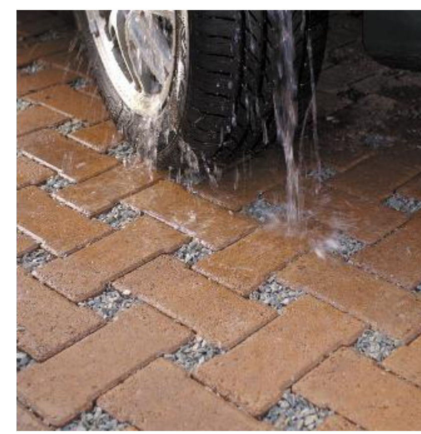


Oke (1987)

<liquidroof.net>

<nissan.com>

<corbisimages.com>



<malamamaunalua.org>

Holistic Urban Energy Models

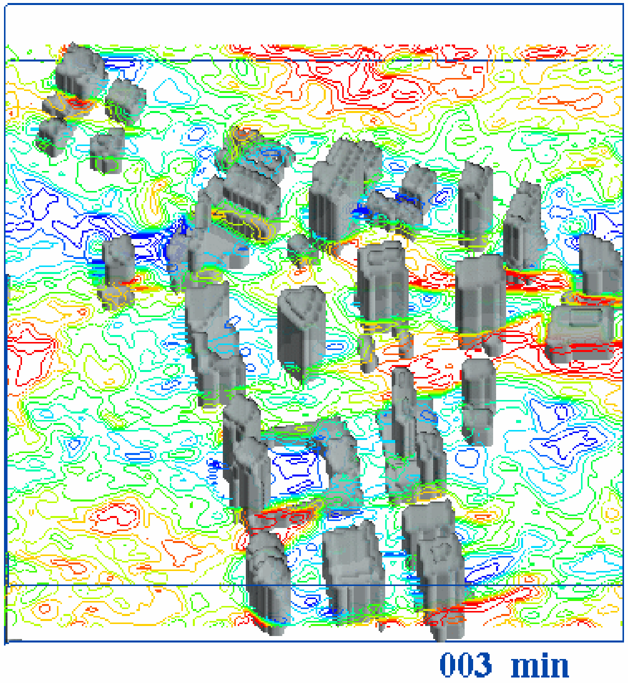
- Coupled conduction, radiation and fluid mechanics models (CFD) with meteorological and materials data in geometrically complex urban domains
- Necessary to evaluate complex feedbacks resulting urban design strategies
  - e.g. “white roads”

Large Eddy Simulation (LES)

- Powerful approach to model turbulent fluid motions over large spatial domains of O(km)
- Deterministically solve the Navier-Stokes equations for large scales of turbulence O(m)
- Apply a Sub-grid Scale *model* for fine scales of turbulence O(cm)
- Computationally cheaper than direct numerical simulation (DNS)

Large Eddy Simulation (LES)

LES of wind speed contours – Shinjuku Ward, Tokyo, Japan
(PALM; Raasch and Schroter, 2001)

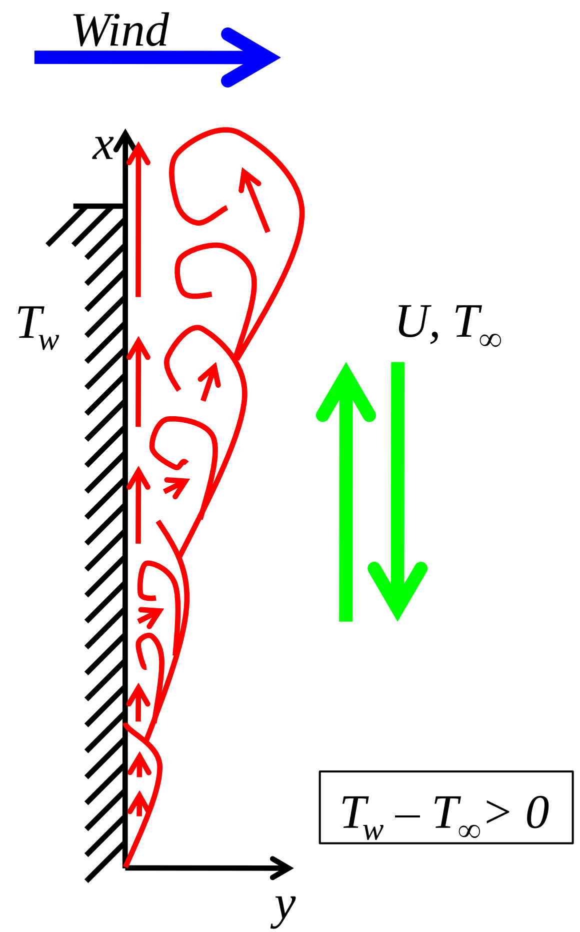


Red = High speed fluid
Blue = Low speed fluid

Kanda Laboratory, Tokyo Institute of Technology (2005)

What about the wall?

- Near wall heat and mass transport cannot be resolved using LES because the energy-containing scales become much smaller than the grid size O(cm) to O(mm)
- Specialized models called *wall functions* are necessary to estimate the convective surface fluxes



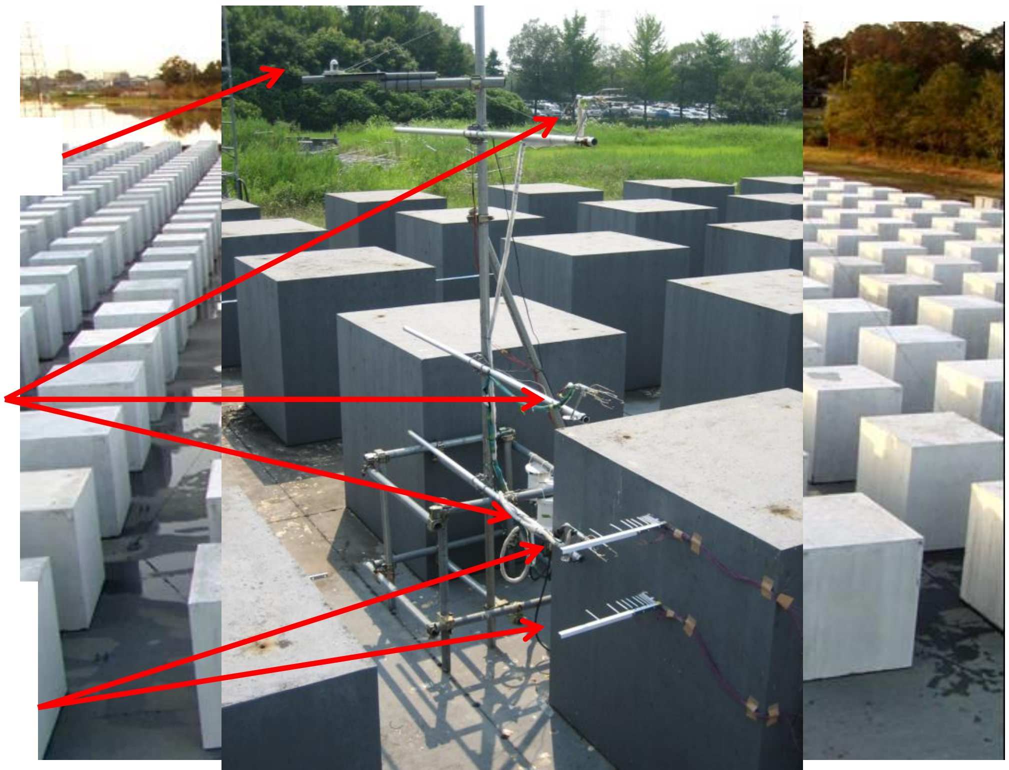
Measurement of wall turbulence

- Comprehensive Outdoor Scale Model (COSMO) for urban atmospheric studies

Pyranometer

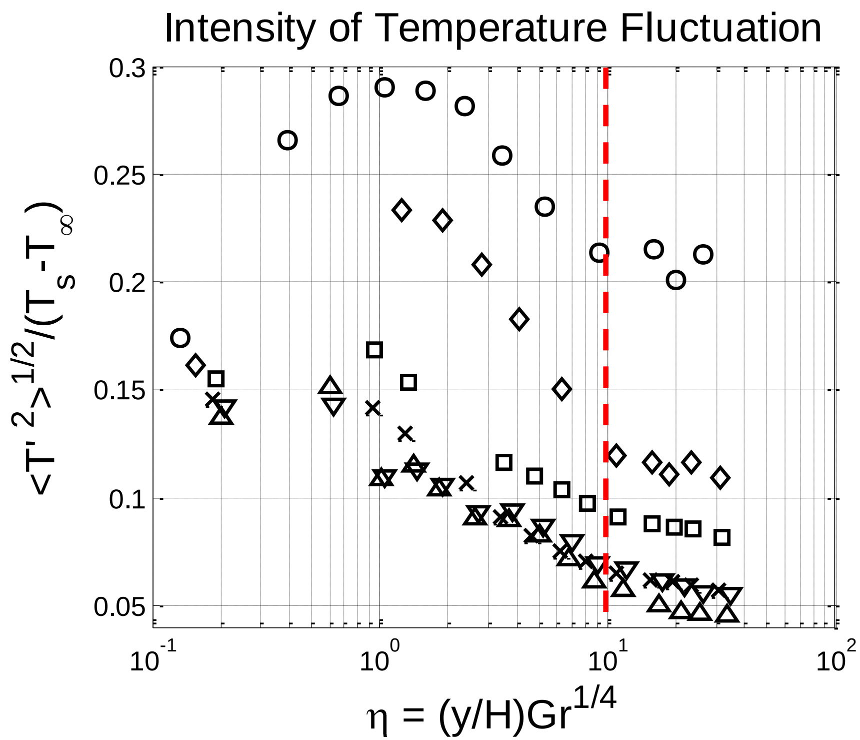
Sonic Anemometers

Fine-wire Thermocouple Rakes (32 sensors)



Kanda (2005) Nottrott (2010)

Characterization of wall boundary layer

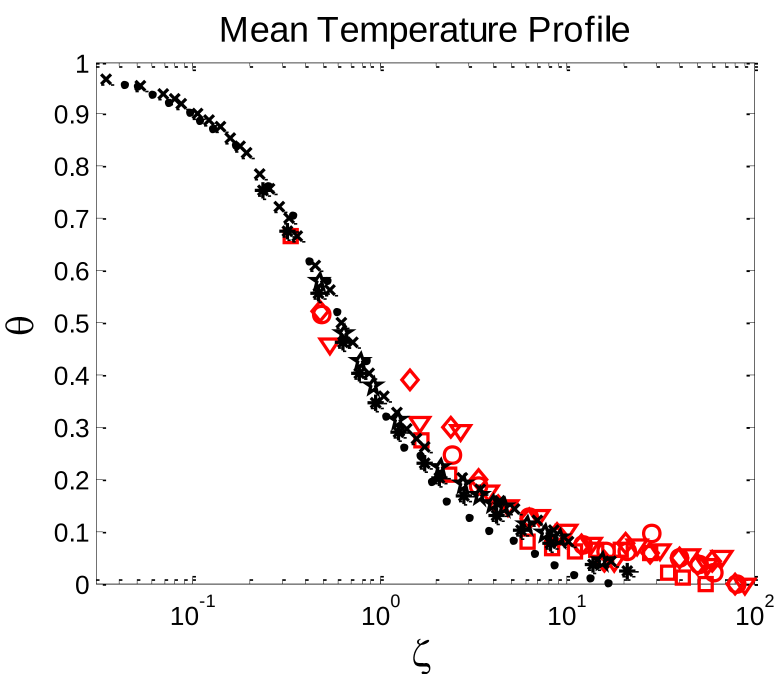


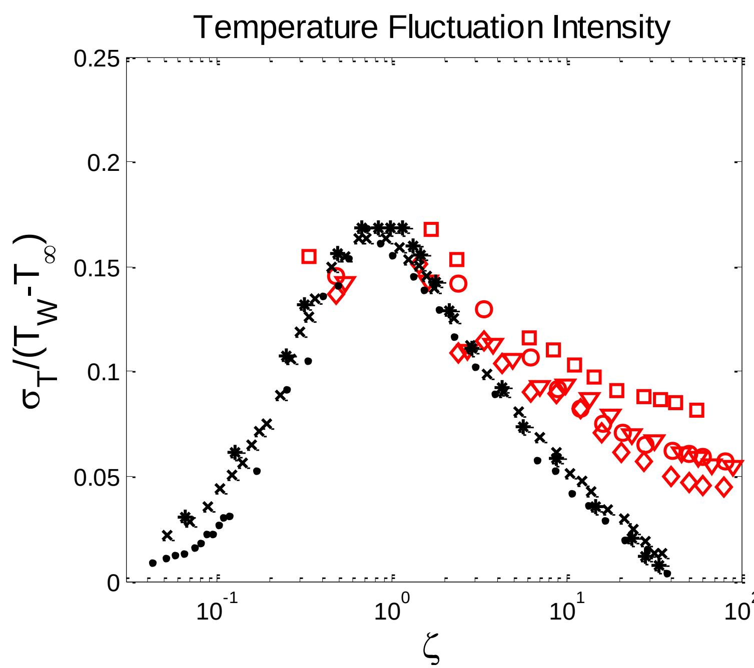
Nottrott (2010)

~ 6 cm from the wall

Characterization of wall boundary layer

- Average boundary layer profiles are consistent with natural convection

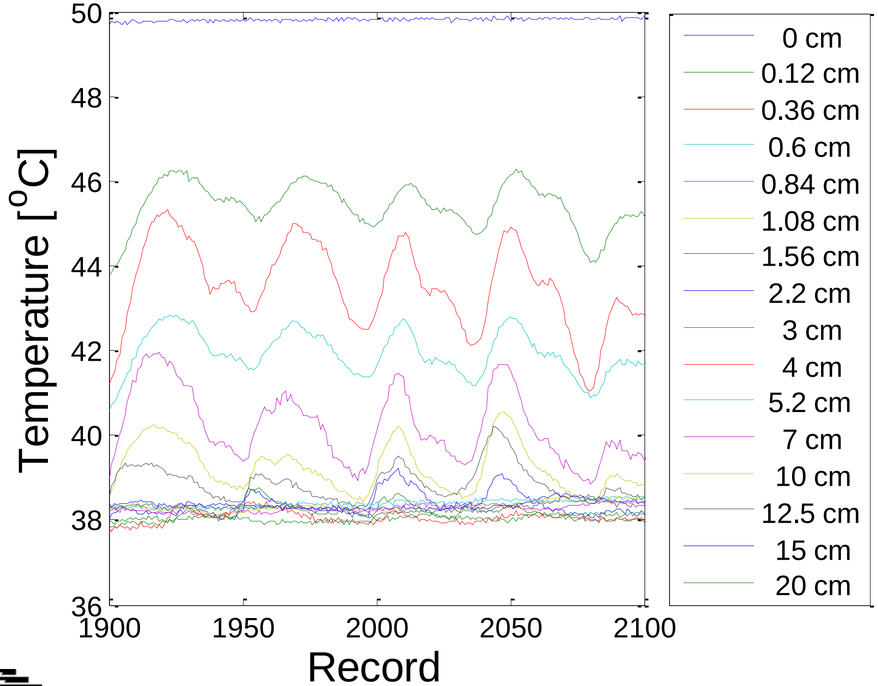


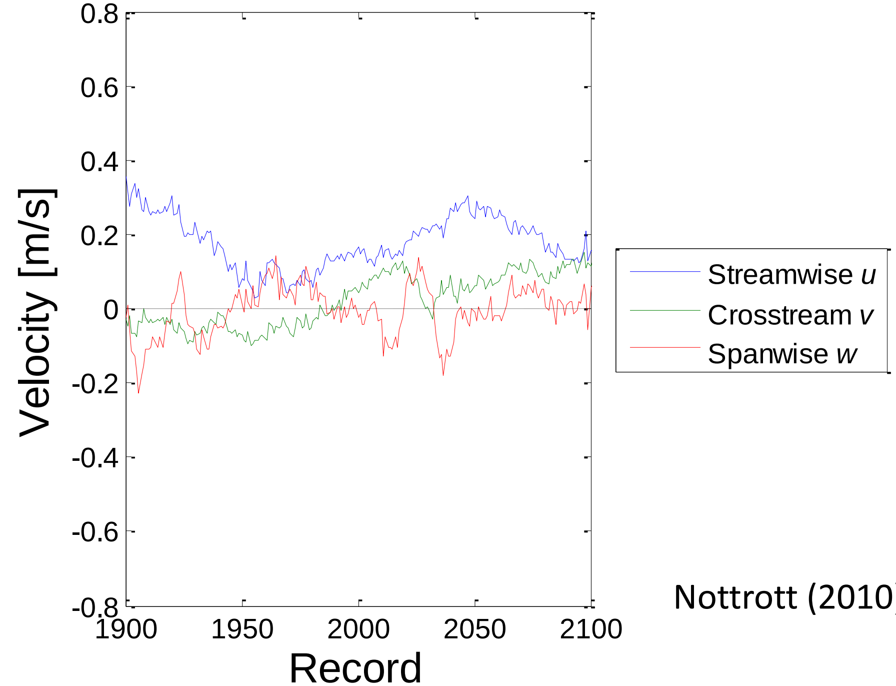


Black = Data from previous studies (adapted from Tsuji & Nagano, 1988)
Red = Data from the present study (Nottrott *et al*, 2010)

Natural convection mode

- In natural convection temperature waveforms are periodic
- Frequency of signal is related to the scale of structures in the boundary layer

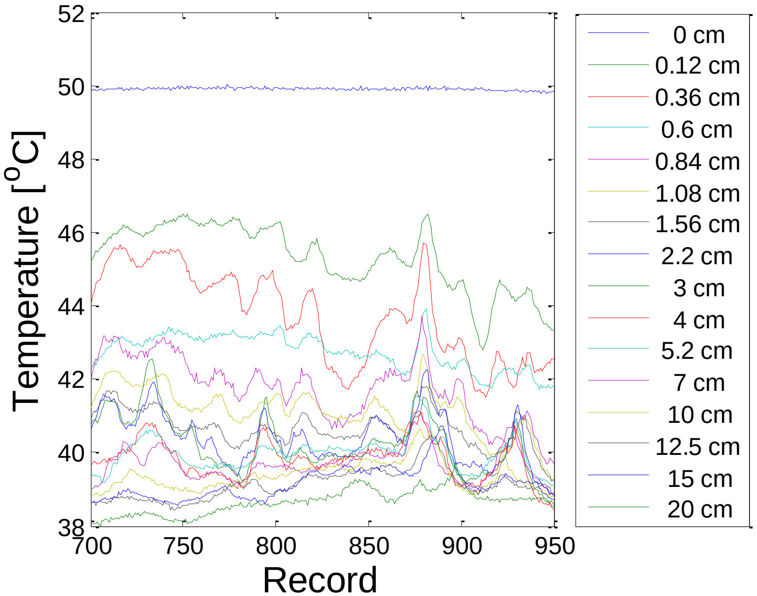


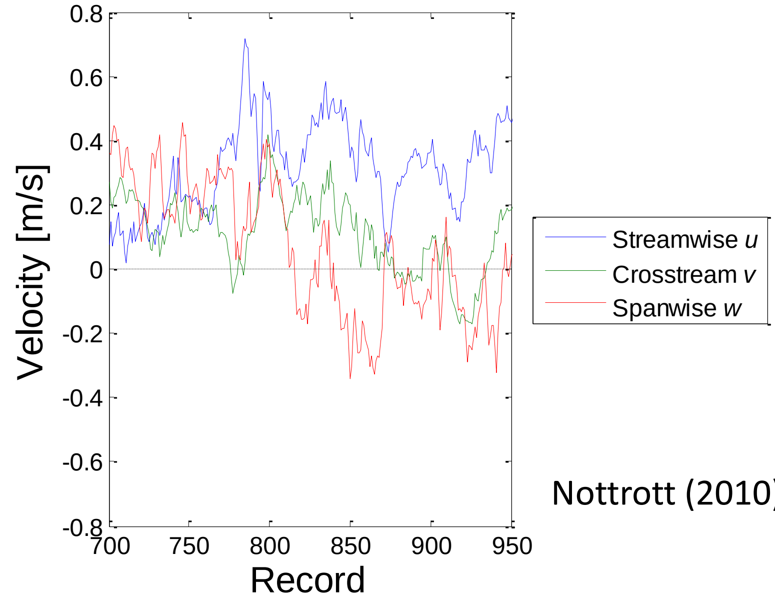


Nottrott (2010)

Forced convection mode

- Upward gust of wind caused transition from natural to forced convection
- In forced convection waveforms are spiky and random





Nottrott (2010)

Conclusions

- Holistic urban energy models must combine energy balance calculations with CFD
- Simplified convection models (wall functions) are used to estimate surface fluxes
- Accurate wall function parameterizations are difficult in urban environments where complex geometries and flow patterns exist

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